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SEARCH FOR TEMPORAL STRUCTURE IN X-RAYS FROM SCO X-1

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ABSTRACT

We have investigated the temporal behavior of the x-ray emission from Sco X-1 on 3 March 1969, based upon data obtained over a continuous 122 sec exposure in the energy range 2 - 20 keV, where the count was recorded each 322 μsec. We find no evidence for any temporal structure in the data. The 5 σ upper limits on the pulsed fraction at any given period are below 1% for periods in the range 3 - 300 msec. We also establish upper limits for non-periodic variations over times from a fraction of a msec to about 1 minute. Any continuous x-ray flickering on the scale of seconds is less than 1.2%, which is below the 0.02 mag. flickering level previously observed in the visible.

I. INTRODUCTION

Temporal variations in the intensity of a cosmic x-ray source provide critical evidence regarding its physical nature. The outstanding such example is the pulsar in the Crab Nebula, NP 0531, which has greatly advanced our understanding of the energy balance for that nebular supernova remnant. Another source, Sco X-1, has exhibited many variable features in the optical, x-ray and radio (Hiltner and Mook, 1967; Lewin, et al. 1968; Ables, 1969).

The best studied intensity fluctuations from Sco X-1 have been in the visible. One class of such fluctuations consists of flare-type increases with typical amplitudes of about 0.2 mag and with time constants of about 10 minutes (Hiltner and Mook, 1967; Westphal et al. 1968). Sco X-1 was observed to be in a flaring state about 12% of the time. In addition, Westphal et al. (1968) found this source to flicker, almost continuously, on time scales from several seconds to minutes with amplitudes averaging about 0.02 mag.

Slower variations in the x-ray intensity from Sco X-1 are now well established. A series of simultaneous measurements from rockets (X-ray) and ground-based telescopes (visible) has indicated, on a statistical basis, the existence of some correlation in the corresponding gross intensities (Chodil et al., 1968; Mark et al., 1969). During a balloon flight, Lewin, et al. (1968) have observed a four-fold increase in hard x-rays from this source, with a temporal evolution not inconsistent with that of optical flares. More recently, Hudson et al. (1970) have used x-ray data from an Orbiting Solar Observatory to correlate two such x-ray

events with optical counterparts. They found that a two-fold increase in the x-ray intensity corresponded to a 0.2 mag optical flare.

The optical identification of Sco X-1 was accomplished via the assumption that both the x-ray and optical radiation fluxes arise from bremsstrahlung emission by the same isothermal hot plasma (Sandage, et al., 1966), at least under quiescent conditions. Such correlation between the x-ray and optical intensities during flares would indicate that they are intimately connected even under conditions far from equilibrium. Hudson et al. (1970) have suggested that the flare emission in both bands is the result of bremsstrahlung radiation by the same plasma, where the relative intensities as observed are altered via the attenuation of the visible output by self-absorption at the source and interstellar extinction. If the x-ray intensity tracks the optical for the more rapid fluctuations (flickering), with relative amplitudes comparable to what is seen in flares, we can then expect to find x-ray flickering amounting to about 10 - 20% of the average intensity. However, Westphal et al. (1968) suggest that the optical flickering is probably connected with the energy "pump" heating the plasma and that it may not show detailed correlations with the x-rays from the plasma. On the other hand, the characteristic time scale for energy loss by the plasma might be much smaller than that of the optical flickering measured to date; Neugebauer et al. (1969) find large absorption at infrared wavelengths which, if the isothermal bremsstrahlung hypothesis is correct, would indicate that the radiating region of plasma is only $\sim 10^{9}$cm in size at a density of $\sim 10^{16}\,\mathrm{cm}^{-3}$, thereby providing a relaxation time for energy loss that is $\leq$ 100 ms. This should certainly

give rise to observable x-ray fluctuations if the characteristic time for energy input is as large as the time scale for the observed optical flickering. We might also expect to see observable short-term fluctuations if there is a pulsar in Sco X-1, as has been suggested by Tucker (1969).

We have investigated the temporal behavior of x-rays from Sco X-1 detected on 3 March 1969 during a continuous 122 sec exposure to this source centered at 1003 UT. The results of a spectral analysis of the same data and a description of the experiment have been given elsewhere (Holt, et al., 1969, Boldt, et al., 1969). The temporal information is in the form of the contents of a 3-bit scaler with accumulation and readout times of 302 and 20 μsec, respectively. The detector count rate averaged about 3000 events/sec while pointing at the source. During the exposure, the angle between the detector axis and Sco X-1 was always well within 1 degree, more than an order of magnitude smaller than the angular response of the detector.

II. PROCEDURE

For a data stream for which the mean value of the instantaneous number of counts per temporal bin N_i is $\bar{N}$, we can define:

$$\chi^2 = \sum_{n=1}^{P} \frac{(N_i - \bar{N})^2}{\sigma_i^2} . \qquad (1)$$

If the data stream is temporally structureless, i.e., if the fluctuations in N_i can be attributed solely to Poisson statistics, the variance σ_i^2 can be formally set equal to $\bar{N}$. Furthermore, if the number of temporal bins P is large ($\gtrsim 40$), the χ^2 distribution is approximately normal with expectation value (P - 1) and variance $\sigma^2 = 2(P-1)$.

Let us suppose that the instantaneous counting rate N_i is the superposition of a base rate N_i^0 and a disturbance in the form of an independent Poisson sample M_j which is present for only some fraction β of the time:

$$N_i = N_i^0 + \delta_{ij} M_j . \qquad (2)$$

The mean $\bar{N}$ is then:

$$\bar{N} = \frac{1}{P} \sum_{n=1}^{P} \left(N_i^0 + \delta_{ij} M_j \right) = \bar{N}_0 \left(1 + f \right), \qquad (3)$$

where $\bar{N}_0$ is the mean which would have been observed had there been no disturbance, and f may be interpreted as the consequent fractional increase in the unperturbed average source intensity.

Equation (1) may now be evaluated with the expression for $\bar{N}$ in equation (3), and the hypothesis of $f=0$ tested for consistency. Should $f \neq 0$ but $f \ll 1$, the increase in χ^2 above the expectation value for f = 0 is:

$$\delta\chi^2 = \frac{f(1-\beta)}{(1+f)\beta} \left[\bar{N}_0 f P - 1 \right] . \qquad (4)$$

An expression for the statistical significance of such a disturbance may be stated in terms of the number of standard deviations n from the $f=0$ expectation value for χ^2 and the total number of counts observed $N_T = P\bar{N}_0(1+f)$:

$$\left(\frac{f}{1+f}\right)^2 = \left(\frac{\beta}{1-\beta}\right)\frac{n\sqrt{2P}}{N_T}. \tag{5}$$

Equation (5) may be interpreted as follows: considering first the dependence on β, we see that a smaller pulsed fraction can be detected by this technique if the duty cycle of the disturbance is small (viz. the disturbances are sharp spikes). Similarly, the sensitivity to fluctuations increases as the total number of counts N_T becomes larger. Finally, equation (5) states that, given a total number of events, a higher sensitivity to fluctuations can be achieved by lumping the data in fewer bins (provided that the bin size does not exceed the on-time of the disturbance). Note that if the condition that the bin size chosen is smaller than the on-time is satisfied, the sensitivity is independent of whether or not the disturbance is contiguous or composed of many disturbances such that the net β is the same. This is particularly useful when searching for longer-term fluctuations, and it also applies to the important case of periodic fluctuations where coherent superposition of data according to a known or a test period results in a reduction in the number of temporal bins by the number of folds in the data stream.

III. NON-PERIODIC VARIATIONS

Considering first non-periodic fluctuations, we have examined the data on the basis of temporal units ranging from 20 msec to 2.6 sec. A finer temporal division, although possible, would have resulted in an insufficient average number of events per bin for the direct application of the technique described above. The largest unit of time is dictated by the temporal modulation of the aperture provided by a paddle in front of the detector; this paddle was advanced to a new position every 2.6 seconds. There were five such distinguishable positions, each corresponding to a different effective area. Each paddle position was repeated about 10 times during the exposure to Sco X-1. In Figure 1, we have plotted the 2.6 sec. rates normalized in order to remove the average rate modulation caused by the paddle. Standard errors at each point average somewhat more than 1 percent. Also shown in Figure 1 are the measured angles between the experiment axis and Sco X-1; errors in this measurement have been estimated at $\pm$ .15°. As the initial gradual increase in the counting rate is caused by atmospheric absorption early in the flight, we have included in this analysis only data to the right of the arrow in this figure. The total number of events in the remaining 122 seconds are 333,879; the number of 2.6 sec units is 47. We have concluded that any deviations from constant intensity on this time scale may be attributed to pointing errors alone. Using equation (5) with n = 5, we may set a 5 σ upper limit on the non-periodic pulsed fraction as

$$f \leq \left[\frac{\beta}{1-\beta}\, 1.37 \times 10^{-4}\right]^{1/2}, \qquad (6)$$

which, for $\beta = .5$ (the least sensitive case), becomes $f \leq 0.012$.

The next smaller time unit has been chosen to be about 180 msec, resulting in 14 times as many temporal bins as were used in the previous case. The 5 σ upper limit here is $f \lesssim .023$ for $\beta = .5$. The smallest time scale considered with this procedure is with 5922 20-msec time units. Here the 5 σ upper limit on the pulsed fraction is $f \lesssim .04$, where we have again taken $\beta = .5$. We note that $\beta = .5$ is truly a worst case, as the method is as sensitive to intensity decreases as it is to increases so that β need never be $> .5$ for $f \ll 1$. Note also that β need not be contiguous.

IV. PERIODIC VARIATIONS

In searching for pulsed emission, we have chosen to use a fast-fold algorithm rather than a harmonic analysis because the former allows for a more straight-forward determination of upper limits using the generalized procedure which we have thus far applied to non-periodic fluctuations. We have searched for possible periodicity in the data by fast-folding at all periods in the range 3 - 300 msec, and testing each light curve for deviations from randomness. We chose not to attempt the analysis for smaller periods, as 10% resolution in the light curve is as poor as we felt was reasonable for making meaningful upper limit statements. For trial periods in excess of $\sim$ 10 msec, the temporal resolution used was never worse than 2.5%. For the entire range of analysis, 3 - 300 msec, the 5 σ upper limit for the pulsed fraction f at any given period is about .01 for β = .5. We note that this value is comparable with the upper limits on pulsation set by Friedman et al. (1969) using a harmonic analysis, but it covers smaller periods than the 70 msec minimum period that they considered and includes the 6 ms period predicted by Tucker (1969) for Sco X-1. In addition, we again note that the sensitivity of this procedure increases for smaller values of β, in contrast to the harmonic analysis approach.

V. RAPID FLICKERING

The finest time resolution possible in our data is set by the 302 μsec accumulation time of the scaler associated with each telemetry word. The average number of events per readout is about 1 count (with a scaler capacity of 7) so that, when searching for fluctuations on scales from fractions of a msec to several msec, we find it necessary to use a different type of analysis. This consists of determining the distribution of a large number of scaler readouts and the extent to which this distribution differs (if at all) from the Poisson distribution, which may be written as

$$P_n(\lambda\tau) = \frac{(\lambda\tau)^n}{n!} e^{-\lambda\tau} , \qquad (7)$$

where $P_n(\lambda\tau)$ is the probability of detecting n counts in τ sec when the average event rate is λ events/sec. Since the Poisson distribution is a one parameter distribution (viz., average event rate), we are essentially testing the hypothesis that the data in a certain interval of time are described by a constant event rate. The actual situation is more complicated because the Poisson distribution applies to the ideal case of no dead time. A small but non-negligible dead time accompanies every event, and this dead time alters the probabilities for multiple counts during a given scaler accumulation period. We have obtained a modified distribution which takes into consideration this dead time and may therefore be used in the analysis described above. The suitable modification of the Poisson distribution is

$$P_n(\lambda\tau) = \lambda^n e^{-\lambda(\tau-n\rho)} \sum_{k=0}^{n} \frac{\rho^k}{(n-k)!} (\tau-n\rho)^{n-k} , \qquad (8)$$

where ρ is the dead time of the apparatus associated with each detected event. In this case, ρ was measured to be 2.8 μsec.

The χ^2 values obtained indicate agreement in all cases, which would appear to rule out large fluctuations on time scales above 300 μsec. To obtain a quantitative interpretation of this agreement, we refer to the simplified "on-off" model introduced earlier for candidate disturbances. For such a small number of degrees of freedom the χ^2 distribution is quite asymmetric, so that upper limits for this case are more properly stated in terms of confidence levels than in terms of a number of standard deviations. In figure 2 we have plotted paired values of β and f/β that satisfy the condition that the 98% confidence limit for the hypothesis of Poisson statistics is exceeded. Any fluctuation characterized by parameters which correspond to a point to the right and above the computed curve would have been detected on the basis of this technique. A detectable fluctuation, for example, involves a pulsed fraction $f = .015$ with $\beta = .03$, independent of how this "on-time" is temporally distributed.

VI. CONCLUSIONS

In summary, we have measured the x-ray intensity of Sco X-1 and found no evidence for fluctuations, periodic or not. Any continuous flickering is less than about .01 magnitudes on the scale of seconds to less than .04 magnitudes on the scale of tens of milliseconds. Shorter time scale fluctuations are absent to within the limits given in Fig.2, down to a time scale of about 300 μsec.

These limits severely constrain energy input mechanisms for Sco X-1. In particular, we can conclude not only that there are no x-ray intensity variations comparable to the optical flickering on a time scale of seconds or greater, but that we observe no plasma relaxation on a time scale corresponding to the thermal bremsstrahlung parameters of Neugebauer, et al. If Sco X-1 is a thermal source, therefore, it would appear that the energy input to the plasma must be essentially continuous compared to the time scale for optical variations.

With regard to periodic fluctuations, the 5 σ upper limits on pulsed emission at any given period, in the range 3 - 300 msec, are about .01 for a roughly sinusoidal pulse profile in time, and considerably less (approximately as $\sqrt{\beta}$) for sharper pulse profiles.

FIGURE CAPTIONS

1. Normalized event rates per 302 μsec, averaged over each 2.638 sec. paddle dwell time, as function of time. Also plotted is the angular offset of the detector from Sco X-1 during this exposure.

2. 98% confidence level limit for rapid ($\lesssim$ 300 μsec) fluctuations of duty cycle β and pulsed fraction f. For time scales $\gtrsim$ 10 msec, the procedure outlined in Section II gives a more sensitive measure for fluctuations.

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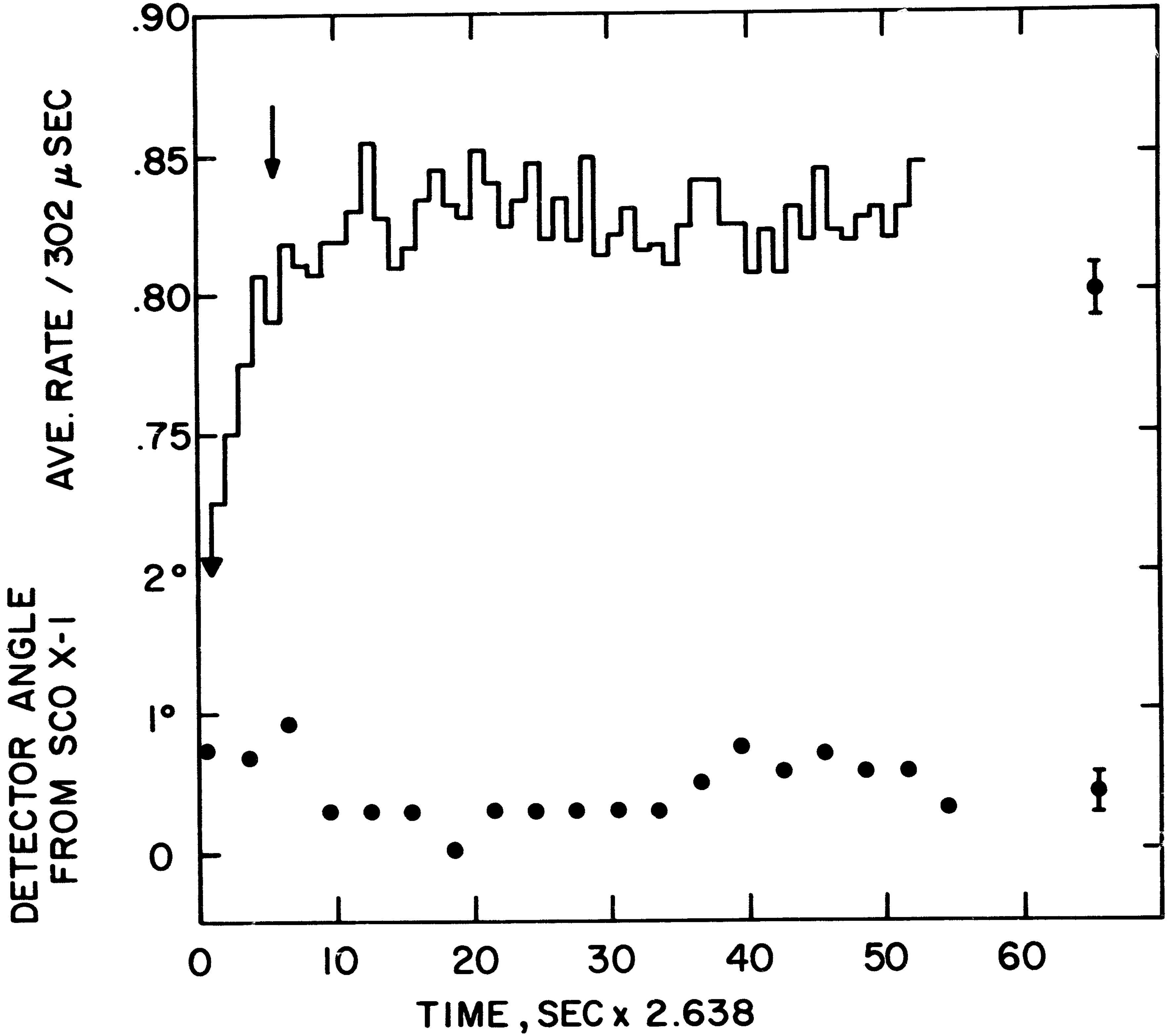
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.85
.80
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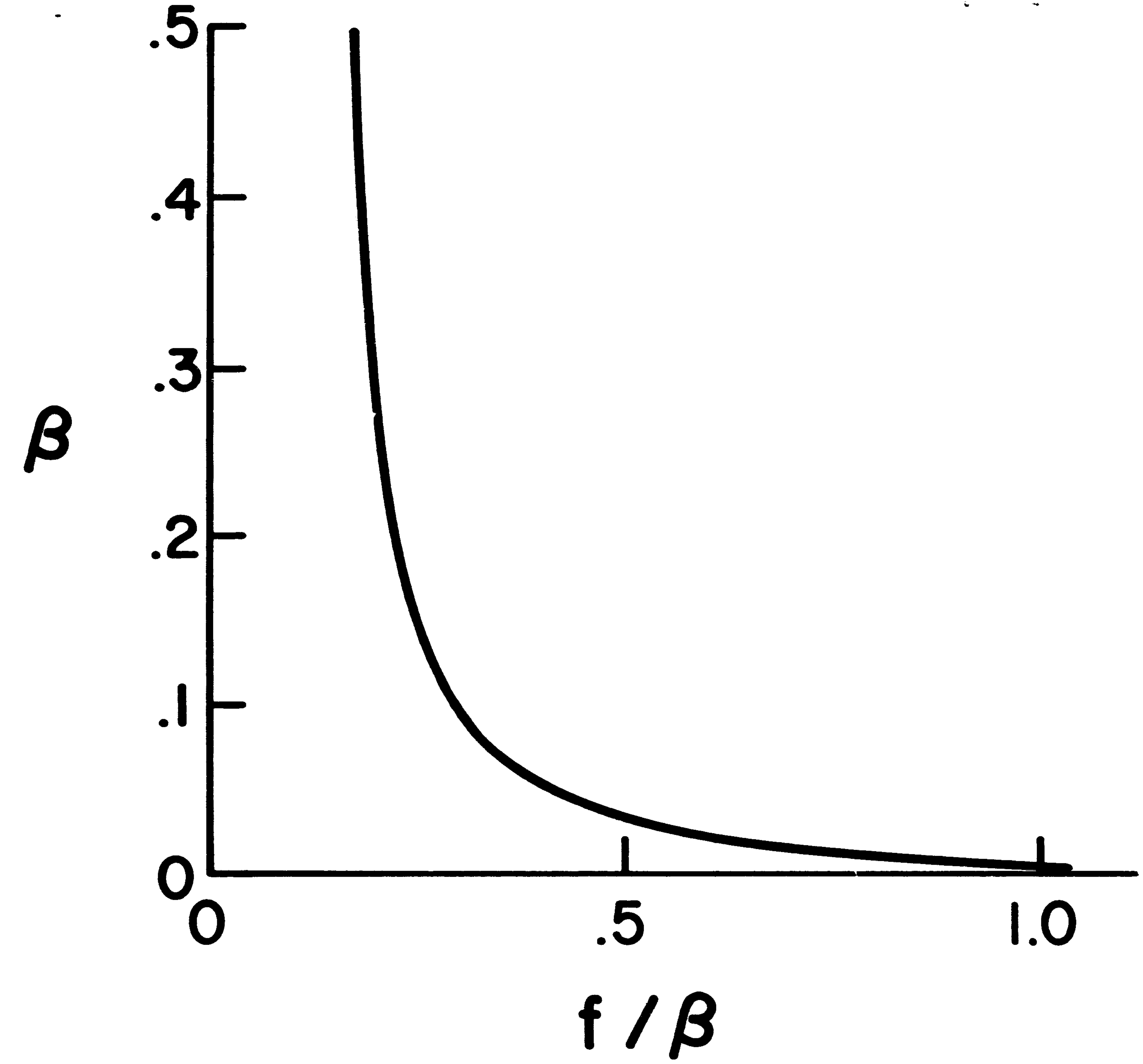
FROM SCO X-1
2°
1°
0
0
10
20
30
40
50
60
TIME, SEC x 2.638



β
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.4
.3
.2
.1
0
0
.5
1.0
f / β